7.1

Habitability and Environmental Factors: the Future of Closed-Environment Tests

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The previous chapters have reported the accomplishments and results from four chamber life support tests completed at NASA Johnson Space Center. Collectively, these illustrate the various interactions of the human with both the habitat and life support systems. Some studies evaluated habitable space as well as air revitalization, water recycling, and advanced technologies such as sensors. In others, the internal environment was evaluated with respect to specific parameters, including noise and human factors. The role of good health practices such as social/psychological, human factors, and food and nutrition was studied in a collective manner. Remote training methods for humans isolated or distanced from traditional instructional techniques and use of telemedicine systems were evaluated. Five major themes emerged from these four tests that were common to those of previous closed-system human life support test projects (1, 2):

- Interdependence of life support systems, habitable space, internal environments, and the human inhabitants
- Importance of testing engineering prototype hardware and advanced technology with "humans in the loop"
- Advances in spacecraft design due to integration of life support testing with human factors, behavior and performance, medical care, training, and life sciences
- Effectiveness of life sciences research with these types of "humans-in-the-loop" ground-based chamber tests; and
- Earth benefits from these types of tests (technology utilization for non-NASA applications).

Interdependence of life support systems, habitable space, internal environments, and the human inhabitants

An example of the interdependence of the water and air advanced life support systems with other activities and systems is illustrated in Figure 7.1-1.

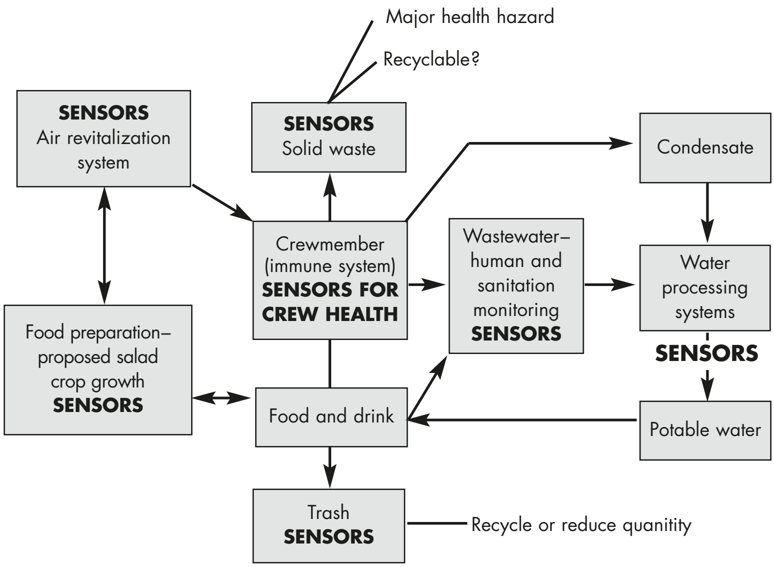

Figure 7.1-1 *An example of the interdependence between systems*

A closed system does not allow for resupply or replenishment of air and water from external sources, thus requiring development and use of technologies for total air revitalization and water recycling. To challenge these systems, the humans participated in a multitude of activities required for normal, healthy living such as physical exercise and food preparation. As NASA plans for very long duration missions, one scenario requires that at least some of the food be grown within the spacecraft using a system designed specifically for such a purpose. NASA has affectionately dubbed one such envisaged system the "salad machine" (Figure 7.1-2). It would be capable of growing foods that could be consumed with almost no preparation. NASA has also proposed utilizing other food systems such as growth of wheat and other grains for use in bread baking. Such activities have both psychological and nutritional benefits for humans in closed life support systems. In the Phase III test, the salad machine and bread baking produced changes in levels of air and water contaminants.

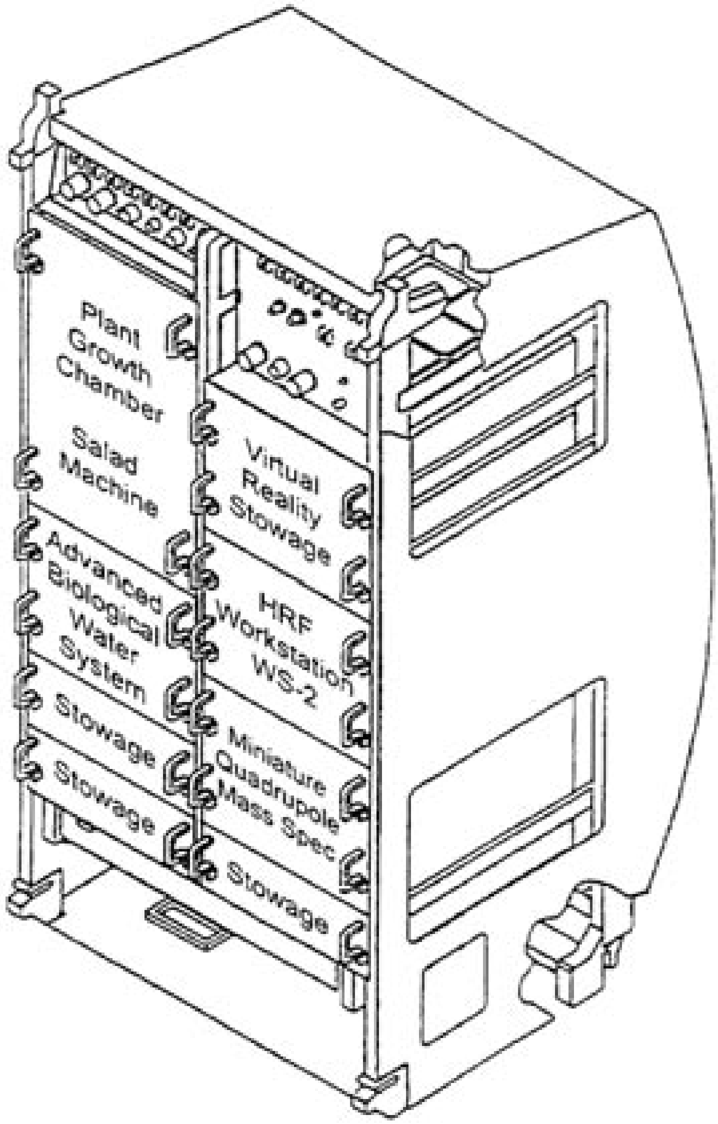

Figure 7.1-2 *The salad machine*

Exercise will be required of all crewmembers participating in long-duration flights. Exercise impacts thermal conditions and air quality (increased heat generation, oxygen consumption, and carbon dioxide generation) as well as increasing water condensate production. The Phase I test demonstrated that exercise enhanced air quality for growing wheat, and at the same time the plants removed some of the carbon dioxide. If major problems occur, such as crewmember noncompliance with the exercise protocol (Chapter 5.2: Exercise Countermeasures Demonstration Projects During the Lunar-Mars Life Support Test Project Phases IIa and III) either voluntarily or due to injury, or in the case of failure of the food system, then the air and water systems must be able to compensate for such events and the resultant environmental changes. Conversely, the pollution of water and air can have deleterious effects on both the plants and crewmembers. Humans also vary their daily schedules. For instance, the crewmembers in the Phases II, IIa, and III tests changed their sleep/wake cycles (Chapter 3.4:Assessment of Sleep Dynamics in a Simulated Space Station Environment), but the engineers supporting the control center outside of the chamber did not. This complicated the crewmembers' psychological/social interactions with the control center personnel, impairing the performance of both (Chapter 3.5: Operational Psychology Countermeasures During the Lunar-Mars Life Support Test Project). Thus, a set of cascading events may affect both the functional capabilities of the life support systems and the crewmembers' ability to effectively and efficiently complete mission objectives. Closed life support chamber tests are effective and practical tools to study such interactions.

Importance of testing engineering prototype hardware and advanced technology with humans in the loop

From the very beginning of these types of tests (1), the influence of the human on the hardware was paramount. These early tests documented the myriad air contaminants that are generated due to long-term human presence. For example, because of bacterial flora in the human intestinal tract, humans are methane producers and as a result methane is a major but only one of many organic contaminants of such closed systems. Human habitation introduces a different set of microbiological contaminants as illustrated in another chapter in this book (Chapter 4.3: Microbiology). Use of sensor technology for environmental monitoring was challenging due to the complexity of the types of compounds encountered. For example, increasing levels of methane and hydrogen strained the sensor's capability to detect other compounds such as formaldehyde (Chapter 4.1: Air Quality). Removal and utilization of water from human wastes continues to be a focus for research (Chapter 4.2: Water Chemistry Monitoring). Humans vary in their level of hydration and this, in turn, affects urine concentration and consequently its specific gravity. Engineering systems must be capable of dealing with extreme variations in urine concentration and specific gravity. Additionally, urine may contain variations in levels and types of nitrogenous compounds as well as metabolites of pharmacological agents prescribed by the medical care team. At the same time, the environmental control system hardware must efficiently use limited resources including nonreplenishable chemicals and energy. Thus, use of these complex closed-loop systems is required in order to make advances in engineering hardware design and to provide an integrated test bed for functional verification.

Advances in spacecraft design due to integration of life support testing with human factors, behavior and performance, medical care, training, and life sciences research

These integrated test beds provide an important analog for advanced technology and research testing. This is clearly documented in the results reported in this book as well as in those from numerous other tests both in the United States and Russia. Operational activities such as space flight, basic research, and advanced life support closed-chamber tests all interact in an interdependent manner as illustrated in Figure 7.1-3.

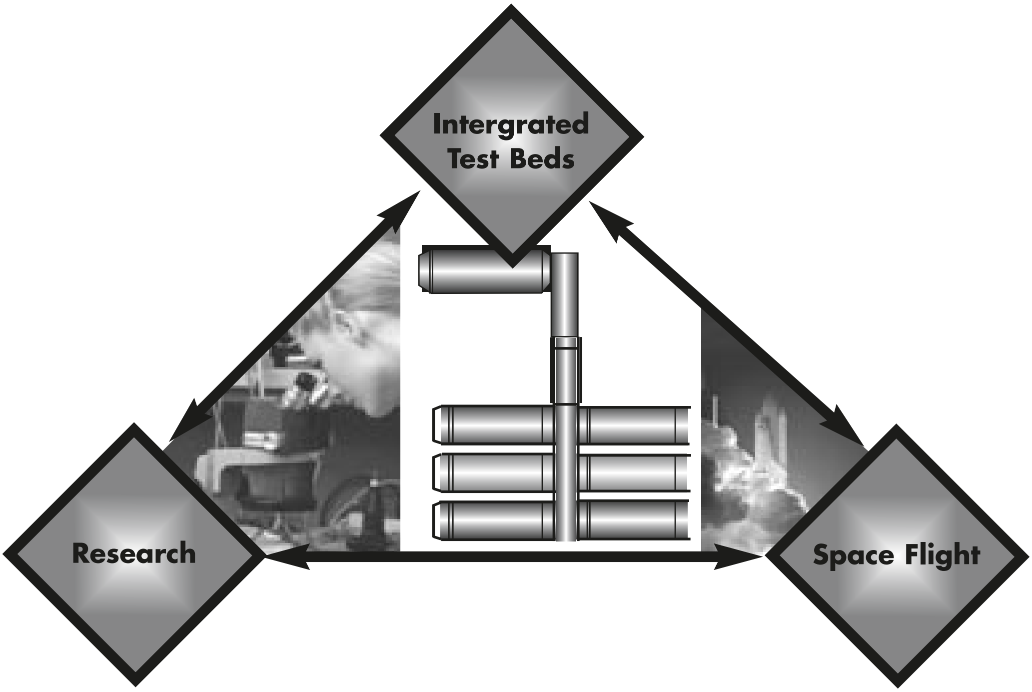

Figure 7.1-3 *Role of ground-based test beds with research and space flight*

The obvious approach to overcoming current barriers is to conduct basic research that will lead to advanced technologies which are first evaluated in ground-based test facilities, then with success become part of operational equipment for space flight. However, space flight operations often redirect research efforts away from original objectives to address more immediate and critical needs. For instance, early in the space program, body weight and bone mass losses were documented. These observations prompted research into the use of pharmacological agents, nutrition, as well as exercise as potential countermeasures (all of which can be partially tested in these life support closed test beds (Chapter 5.1: Nutritional Status Assessment During Phases IIa and III of the Lunar-Mars Life Support Test

Project and Chapter 5.2: Exercise Countermeasures Demonstration Projects During the Lunar-Mars Life Support Test Project Phases IIa and III). Furthermore, the studies from these tests often lead to additional research efforts. For instance, the results from the Phase I and III tests showed that food production, processing, and preparation could be part of the advanced life support systems (Chapter 4.4: Crew Food Systems). However, additional research efforts are needed that focus on the processing of hydroponically grown crops that could be used to recycle air and water. Present food processing practices use enormous amounts of water, a limited resource during space exploration. Basic research is required in production and processing of foods with limited water, and within the necessarily restricted volume and energy resources of spacecraft. Furthermore, foods grown under these conditions may have different physical properties (e.g., level of gluten from flour and nutritional qualities such as mineral components) than otherwise identically Earth-grown foods. This, in turn, requires additional basic research efforts to optimize food production processes to yield foods with appropriate nutritional content.

These test beds also provide an opportunity for human factors research that must consider the limitations imposed by spacecraft volume available for human habitat and its design. Thus, different components of human factors can be evaluated in a totally integrated fashion such as the living necessities of sleeping, eating, working, and use of leisure time (Chapter 3.2: Habitability: an Evaluation). Most human factors studies are directed toward component understandings, but within the environment of these advanced life support tests, such components can be integrated and verified. An example that has been evaluated is the importance of ambient noise level (Chapter 3.3: Acoustic Noise During the Phase III Chamber Test), sleeping space conditions, and personal space requirements (Chapter 3.7: Sociokinetic Analysis as a Tool for Optimization of Environmental Design). The human factors team must consider the combination of engineering and architectural design solutions that provides the bases for these types of research efforts.

These types of test beds also provide a chance to test various procedures in a safe and closely monitored environment. The medical support team can evaluate telemedicine hardware and procedures (Chapter 6.1: Telemedicine During Lunar-Mars Life Support Test Project Phase III), and the effectiveness of just-in-time training (Chapter 6.2: In Situ Training Project: LMLSTP Phase III Report) can be assessed. In the Phase III test, there was a minor medical event that was resolved utilizing the telemedicine and crew training processes (Chapter 2.2: Chamber Studies Medical Care Overview: Medical Officer's Report). Psychologists have used these test beds to evaluate crew teamwork training efforts and as a result were able to improve their astronaut team training, an outcome that is vital for long-duration space flight mission success (Chapter 3.5: Operational Psychology Countermeasures During the Lunar-Mars Life Support Test Project).

To improve understanding of human health and the essential support technologies, NASA Life Sciences teams have developed Critical Path Roadmaps to provide the research programs necessary for improved spacecraft design as well as capabilities to improve crew health. As part of this effort, research and technology development has been categorized into several levels of technology readiness (Table 7.1-1). Within the Critical Path Roadmap, issues and questions are assigned to a specific level of technology development. If basic research is needed, then the efforts are assigned a low-level of technology readiness and the program emphasis is enabling research. Other more mature technologies are assigned a higher level of technology readiness. As important technologies are developed, the program determines whether these technologies should be tested in the laboratory or in a relevant environment such as in these ground-based test beds. Finally, after verification in the relevant environment, a subsystem prototype can be tested in a space environment or implemented as part of standard spacecraft operations.

Table 7.1-1 *Technology readiness levels*

Level	Definition
TRL 1	Basic principles observed
TRL 2	Technology concept and/or application formulated
TRL 3	Analytical and experimental critical function/proof-of-concept
TRL 4	Component and/or breadboard validation in lab
TRL 5	Component and/or breadboard in relevant environment
TRL 6	System/subsystem model or prototype demonstration in relevant environment
TRL 7	Subsystem prototype in a space environment
TRL 8	System completed and flight qualified through demonstration
TRL 9	System flight proven through mission operations

Effectiveness of life sciences research with these types of human-in-the-loop ground-based chamber tests

Life sciences research has benefited immensely both from ground-based chamber tests and from use of other types of test beds as scientific analogs to space flight and of other semi-isolated conditions such as polar ice stations, submarines, submersibles, etc. For instance, the findings from previous studies have shown changes in human sleep cycles, immune function, and psychological adaptations. Thus, certain features are shared between operational scenarios and ground-based chamber tests in the human participants. However, differences may exist as well. For example the exercise protocols used in Phases IIa and III had a different outcome than in a non-enclosed environment. Specifically, the exercise protocol tested in the Phase III test resulted in an overuse injury that is usually associated with training for athletic events. Thus, the psychological and social roles of exercise may differ depending on the environment in which the exercise is performed. Determining both the shared and different features that exist between ground-based analogues and operational environments is important for future studies. More emphasis can then be placed on acquiring a better understanding of changes in human physiology and psychology that are common to operational environments and closed-chamber tests. These common features can be more completely studied in controlled ground-based studies. Equally important is knowledge of the differences that may exist between the environments so that these differences may be considered in the interpretation of the results of all studies. Closed-chamber tests with humans in the loop lead to new technologies for monitoring and for countermeasures to untoward effects of isolation. Technologies that have the potential to enhance nonintrusive monitoring of individual and group performance may have a positive impact on enhancing crew performance (Chapter 3.6: Spaceflight Cognitive Assessment Tool for the Lunar-Mars Life Support Test Project Phase III Test). Thus, future research may place more emphasis on additional specific concerns.

Earth benefits from these types of tests (technology utilization for non-NASA applications)

Table 7.1-2 illustrates some of the Earth benefits from the test results reported in this book.

Table 7.1-2 *Earth benefits from recent advanced life support tests*

Area	Examples
Habitability	Designing living space for maximum human performance Tools for evaluation of safety of habitat
Psychological/Social	Noninvasive methods for measurement of circadian rhythms and sleep quality Tools for tracking crewmember's psychological health and team work Evaluation of psychological status in isolated environments Cognitive assessment tools
Engineering design	Tools for movement patterns of groups within controlled and limited environmental design
Air and water quality	Importance of trend analysis for air and water quality Water recycling methodologies including microbiological, metals, and organic compound measurement technologies Problems related to cleaning of surfaces when dependent on air recycling/indoor air quality Wearable detectors for air quality, e.g., formaldehyde sensors

Table 7.1-2 continued *Earth benefits from recent advanced life support tests*

Area	Examples
Food systems/nutrition	Food processing with water limitations and air recycling Utilization of food frequency questionnaires as a dietary assessment tool Palatable diet with vegetarian diet and/or limited variety of foods
Exercise	Effectiveness of aerobic exercise with resistive exercise; overtraining
Microbiology and medicine	Decreased immune responsiveness with latent viral reactivation under stressful and isolated conditions
Medicine	Utilization of telemedicine with untrained crewmembers in isolated conditions
Training/Education	Just-in-time learning and evaluation of different types of training: video, computer-based, virtual reality

The Future

There is no doubt that larger and more fully integrated tests are required to validate exploration-class and low Earth-orbit mission scenarios. The principle that guides these efforts is technology-based and is illustrated in Figure 7.1-4. The next generation of technologies draws from the evolving knowledge base in information technology. Advances in information technology will improve analysis and manipulation of data and will provide biocomputations for image analysis and essential training simulation efforts utilized for medical support through telemedicine. Information technology research may elicit understanding of the control systems for the large variations in human activities, yet at the same time minimize the hardware, energy, and resupply needs. The ongoing modeling efforts to determine the best combination of systems must be evaluated in an integrated test bed before they can be utilized in Earth-orbital or exploration-class missions. Advances in biotechnology will result in improved sensors, and new developments in micro- and nanotechnology will provide the basis for design and construction of better hardware for maintaining a closed life support system (Figure 7.1-5). With highly reliable autonomous life support systems, the spacecraft can ensure a breathable atmosphere, potable water, food production, solid/water processing, and thermal control. Through the automatic detection and remediation systems, microbial and chemical contaminations due to humans, food processing, and waste management can be controlled (Figure 7.1-6). Future research in microbiology and immunology (Chapter 4.3: Microbiology; Chapter 5.3: Reactivation of Latent Viruses; and Chapter 5.4: The Influence of Environmental Stress on Cell-Mediated Immune Function) is needed, as this is an important area given the experimental nature of the air revitalization, water recycling, waste management, and food processing activities that will occur within these small, enclosed systems. Figures 7.1-4 and 7.1-5 illustrate some examples of the requirements for ongoing efforts in micro- and nanotechnology development. Critical research areas include development of adaptive user interfaces and displays, onboard systems for refresher training and skills monitoring, continuous assessment of mental status and, of course, personal communications and recreation through integrated systems (Figure 7.1-7). As seen from Figure 7.1-4, the goal is to move from a strong human interface with the life support system not just to an automated system requiring little direct human intervention, but rather to a self-analysis system, and then finally to a self-repairing system. This will lead to decreased hardware mass requirements that reduce launch mass, a critical concern for efficient achievement of low Earth orbit. Finally, a major benefit is that crew time can be used for exploration and scientific missions rather than for repair, maintenance activities, training, and health monitoring. Critical areas for future research include habitation systems, such as advanced life support, environmental health, food and nutrition, and human behavior and performance. However, besides these basic areas for research, ground-based closed-system test beds are excellent analogs for improving and verifying clinical care capabilities and multisystem integration (Table 7.1-3).

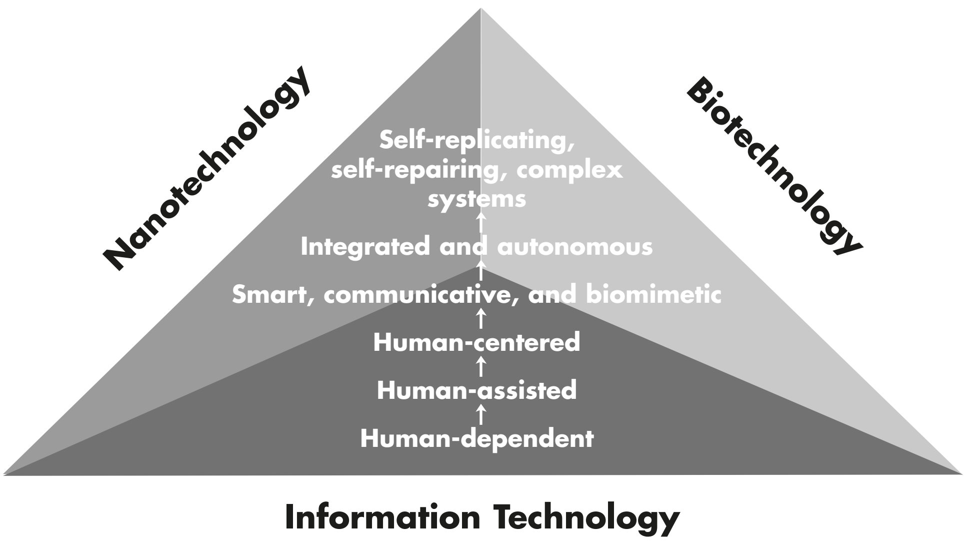

Figure 7.1-4 *Technologies of the future*

Life support
- Sensors and effectors
- Bioregeneration
- "Human-on-a-chip"
- Biological niches

Medical care
- Diagnostic probes
- Treatment and delivery systems
- "Keyhole" surgery
- Tissue replacement

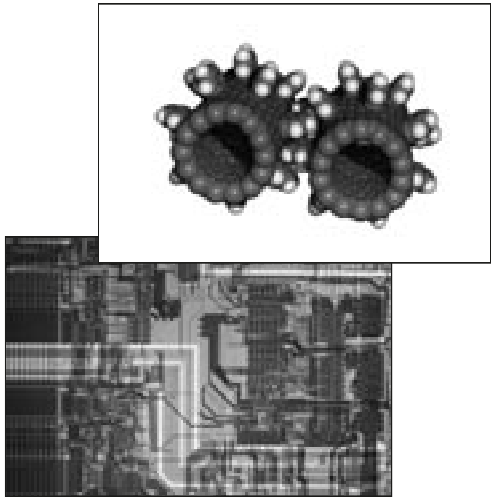

Figure 7.1-5 *Nanotechnology: research and design at the molecular level*

Highly reliable, autonomous life support systems to provide:
- Breathable atmosphere
- Potable water
- Crop production and processing
- Solid waste processing
- Thermal control

Automatic detection and remediation of environmental factors
- Microbial and chemical contamination in air, water, and food
- Radiation events or cumulative exposure

Figure 7.1-6 *Critical area: advanced life support.*
Image courtesy of Bob Sauls of John Frassanito and Associates

- Nonintrusive monitoring of individual/group performance
- Adaptive user interfaces and displays
- Onboard systems for refresher training and skill monitoring
- Continuous assessment of mental status
- Personal communications and recreation through integrated systems

Figure 7.1-7 *Critical area: crew performance. Computer-generated image courtesy of Bob Sauls of John Frassanito and Associates*

Table 7.1-3 *Critical areas for research*

Function	Discipline Risk Areas
Habitation systems	Advanced life support Environmental health Food and nutrition
Adaptation/Countermeasure systems	Bone loss Cardiovascular alterations Human behavior and performance Immunology, infection, and hematology Muscle alterations and atrophy Neurovestibular adaptation Radiation effects
Medical care systems	Clinical capabilities Multisystem (cross-risk) alterations

NASA's future plans include a much larger closed life support system potentially composed of six chambers – 15 ft in diameter by 37 ft in length with a 12 ft diameter, 63 ft long tunnel, and a 1.5 ft long node 12 ft in diameter (Figure 7.1-8). The six chambers are interconnected yielding an internal volume of approximately 44,000 ft^3.

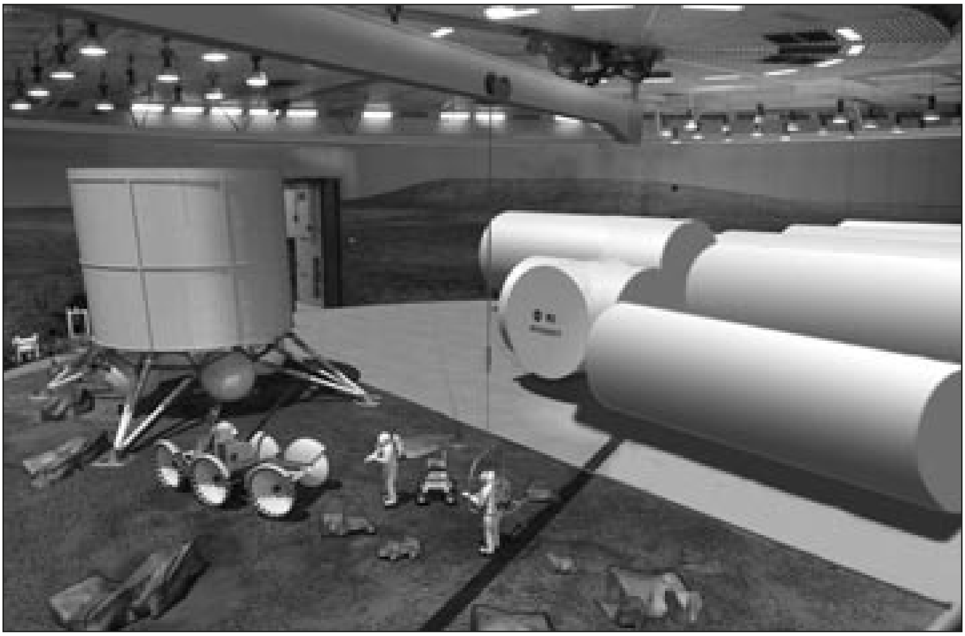

Figure 7.1-8 *An artist's rendering of a future closed life support systems test bed. Image courtesy of Bob Sauls of John Frassanito and Associates*

The goal is for all systems (i.e., air, water, power, thermal control, waste management, plant production, food processing, and human habitat) to be contained within the chambers. This will provide the capability for monitoring mass balance and for acquisition of the data necessary to enhance modeling of life support systems for long-duration space flight. A laboratory chamber is proposed that will provide chamber air, water, and other essential monitoring and analysis. This effort will require development of micro- and nanotechnologies since inadequate space exists for traditional analytical instrumentation. The integrated test system will have a control room adjacent to it for monitoring and control of the series of planned tests. The major driver for development of this large ground-based closed life support test bed is to provide capabilities for integrated tests of advanced life support engineering: water recycling, air revitalization, waste management, crop production, food processing, and thermal management within a closed system. Advanced sensors and new types of information technologies along with modeling technologies will be routinely tested and verified. Beyond these activities, additional studies are planned that will include human factors research.

Confinement is an analog for several avenues of research including psychological, immunologic, and training studies. Additionally, confinement can provide a good model for research into the effects of light on human subjects. Historically, little attention has been given to mimicking the intensity and spectral output of sunlight, despite our knowledge that intensity and duration of light can have significant effects on circadian rhythms and that ultraviolet B radiation is required for vitamin D biosynthesis. Light conditions similar to those found on the Martian and lunar surfaces can be simulated in these test chambers. Furthermore, the limited and delayed communications expected with exploration-type missions can be mimicked to provide improved communication methodologies necessary for effective psychological and medical support.

Conclusions

Each chapter of this book reflects the types of investigative activities that can benefit from closed life support chamber studies. As advances in space flight-related sciences, technologies, and engineering approaches occur, these can be evaluated in a long-duration integrated test in order to more clearly define the interactions between systems. Critical areas of life sciences research are listed in Table 7.1-3. It is important to continue ground-based systems testing within these critical areas if the reality of human exploration of our solar system – and ultimately beyond – is to be achieved.

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